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HIGH-SPECIFIC-IMPULSE GAS-CORE REACTORS

by Robert G. Ragsdale

Lewis Research Center
Cleveland, Ohio 44135

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16. Abstract

Calculations are carried out to estimate gas-core nuclear rocket engine weights for specific impulses ranging from 3000 to 7000 seconds, and for engine thrusts ranging from 4400 to 440 000 newtons. Engine weight was found to vary from 35 000 to 270 000 kilograms, for the entire range of specific impulses and thrust levels of this study. This engine weight range corresponds to a specific mass that varies from 0.6 to 0.02 kilogram of weight per kilowatt of thrust power.

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SUMMARY

Virtually all existing or proposed rocket propulsion engines can be categorized as either high-thrust systems or high-specific-impulse systems. What is really needed for fast interplanetary travel is both characteristics, namely a high specific impulse (3000 sec or greater), and an engine thrust-weight ratio that is in the range from 10^{-2} to 10^{-1}. The characteristics of a gas-core nuclear rocket engine are examined in this study to see how closely it meets these requirements.

Calculations were carried out to estimate gas-core engine weights for specific impulses ranging from 3000 to 7000 seconds and thrust levels from 4.4×10^{3} to 4.4×10^{5} newtons. A vapor-fin space radiator operating at 1100 K was incorporated into the engine system to dispose of waste heat not regeneratively removed by the hydrogen propellant. The total engine weight was composed of the individual weights of the radiator, the reactor moderator-reflector materials, the pressure shell, the nozzle, and the propellant turbopump. The study produced the following results and conclusions:

1. Gas-core engines have the potential of producing a specific mass in the range 0.6 to 0.02 kilogram of weight per kilowatt of thrust power.

2. For a specific impulse of 5000 seconds and a thrust of 1.1×10^{5} newtons, engine weight is estimated to be 91 000 kilograms. This weight is composed of about equal proportions of radiator, moderator, and pressure shell weights. For the entire range of specific impulses and thrust levels of this study, engine weight varied from 35 000 to 380 000 kilograms.

3. Engine weight increases with increasing specific impulse and with increasing thrust level. For a given specific impulse, higher thrust-weight ratios occur at higher thrust levels because engine weight does not increase as fast as the thrust does.

INTRODUCTION

Reference 1 points out that virtually all existing or proposed rocket propulsion systems can be put into one of two general classes. Type I systems produce high thrust, but are limited to specific impulses less than 1000 seconds. Type II systems produce specific impulses of thousands, or even tens of thousands, of seconds, but are limited to thrusts less than 45 kilograms. For fast interplanetary travel a third class is needed, or at least would be highly desirable. This "Type $I\frac{1}{2}$" engine should provide both high specific impulse and high thrust. The characteristics of a gas-core nuclear rocket engine are examined in this report to see how closely it meets these requirements.

The gas-core work is aimed at a basic feasibility evaluation of the engine concept. It is not a development program. The idea of a gas-core nuclear rocket engine is not new; related research studies have been underway for over a decade. Most of the work has been in the disciplines of fluid flow, radiant heat transfer, and reactor physics, although some attention has been directed to engine studies (refs. 2 to 4). A recent symposium covered most of the gas-core technology, as well as other topics related to gaseous uranium plasmas (ref. 5).

There are currently two concepts of how to make a gas-core reactor. One idea is to allow direct contact between the uranium plasma and the surrounding stream of rocket propellant, hydrogen. This "open-cycle" engine concept is under investigation at the Lewis Research Center and is the subject of this report. A second gas-core idea is to incapsulate the uranium plasma within a solid but transparent material. This "closed-cycle" engine is being studied at United Aircraft Research Laboratories. A recent summary of this work is available in reference 6.

To date the goal of gas-core work has been to evaluate the feasibility of an engine with a specific impulse in the range 1500 to 3000 seconds and a thrust equal to, or greater than, the engine weight. A recent study (ref. 4) indicated that a 1.76×10^6-newton-thrust, 1800-second-specific-impulse engine would weigh approximately 130 000 kilograms for a hydrogen- to uranium-mass-flow ratio of 100 and a critical mass of 50 kilograms. The study did not consider specific impulses above 3000 seconds or thrusts below 4.4×10^5 newtons. The engine critical mass was treated as a parameter in the calculations. The fuel volume in the engine cavity was taken to be a specific function of the hydrogen- to fuel-mass-flow ratio; the equation used was based on the most recent fluid mechanics experimental information available at the time.

New information is now available. First, the range of interest in gas-core engines has been extended to specific impulses above 3000 seconds. This requires that a space radiator be incorporated into the engine scheme. Second, enough gas-core nuclear information is available so that critical mass no longer has to be treated as a parameter (ref. 7). Third, some recent fluid mechanics experiments using air/air have indicated that the fuel region in a gas-core engine may be 25 percent of the cavity volume for hydrogen- to uranium-mass-flow ratios in the range 100 to 400. Fourth, some unpublished work done at Lewis indicates that a gas-core rocket reactor with a specific impulse in the range 3000 to 7000 seconds and a thrust in the range 2.2×10^4 to 2.2×10^5 newtons may represent a new, interesting, and unique kind of space engine for certain classes of missions.

This report examines this new kind of a gas-core engine, with a high specific impulse and a low thrust. This study extends the range of specific impulse (upward) and thrust (downward) studied in reference 4, and at the same time updates the fluid mechanics and nuclear inputs to the engine analysis. Specifically, this present report discusses the principle of operation of a gas-core engine with a space radiator, gives the specific impulse characteristics of the engine, and presents engine weight estimates as a function of specific impulse and thrust level.

PRINCIPLE OF OPERATION

Like the solid-core nuclear rocket engine, the job of a gas-core engine is to produce hot hydrogen and then expand it through a nozzle to convert the thermal energy into thrust. In order to obtain a higher specific impulse than the 825 seconds of the solid core, a gas core has to produce hotter hydrogen. For a specific impulse of 825 seconds, the hydrogen temperature at the nozzle inlet is approximately 2500 K. A temperature of 8300 K is required for a specific impulse of 2500 seconds; 22 000 K is required for a specific impulse of 5000 seconds. These temperature levels required for high specific impulse cannot be obtained by simply running solid-core-type fuel elements at a higher temperature.

The gas-core concept is to use an incandescent, radiating ball of fissioning uranium plasma as the "fuel element." The nuclear heat released within the uranium plasma leaves its surface in the form of thermal radiation, or photons. This thermal energy is picked up by a surrounding stream of hydrogen propellant, which is then expanded through a nozzle to produce thrust.

Figure 1(a) illustrates schematically how this basic notion might be translated into a rocket engine. It is not unreasonable to picture this kind of engine as a nuclear "sun" with the central fireball and surrounding gas flow contained within a chamber surrounded by structural materials. The analogy is not exact, of course, because the heat generation is due to nuclear fission rather than fusion. However, in both cases the amount of energy that can be generated in, and released from, the fireball is essentially unlimited. There is, however, a limitation on how much energy can be absorbed by the hydrogen and turned into thrust without overheating the cavity wall or the exhaust nozzle. It is the amount of energy that reaches various solid, temperature-limited regions of the engines that ultimately limits the power generation and therefore the specific impulse.

The proposed reactor shown in figure 1(a) is basically spherical. It is composed of an outer pressure vessel, a region of heavy-water reflector, a high-temperature beryllium moderator region, an inner heavy-water moderator, and finally a porous or slotted cavity liner. Approximately 7 to 10 percent of the reactor power is deposited in these solid regions of the reactor due to attenuation of high-energy gamma and neutron radiation. This heat is removed either by a coolant in an external space radiator loop, or regeneratively by the hydrogen propellant before it enters the central reactor cavity, The beryllium region is operated at a temperature of about 1300 K and the radiator at 1100 K.

The hydrogen is pumped to a pressure of 5.07×10^{7} to 10.14×10^{7} newtons per square meter by means of a turbopump operated by hydrogen bled from an intermediate station in the propellant circuit. The hydrogen then is ducted into the spherical plenum behind a porous or slotted wall. Appropriate seed particles which are about the size of smoke particles are introduced into the hydrogen as it enters this plenum region. The seeded hydrogen then flows through the porous or slotted wall. By properly designing the shape of the porous wall and by proper injection and distribution of the hydrogen flow through this wall, a relatively stagnant nonrecirculating central region forms within the cavity. The cavity is about 2.4 meters in diameter. The central fuel region occupies about one-half of the cavity volume and contains primarily ionized uranium, along with some hydrogen (up to perhaps 50 atom percent) that would diffuse in from the outer edge of the fuel region.

Uranium metal would have to be injected into this high-pressure region. Once inside the cavity, the uranium vaporizes and rises to temperatures sufficient to thermally radiate the energy that is generated by the fissioning uranium. A possible fuel injection technique might consist of pushing a thin rod of solid uranium metal at a high velocity through a shielded pipe (perhaps made of cadmium oxide) that penetrates the moderator. Some cooling of the uranium fuel and the shielded passage may be required to remove the heat that would be generated in the fuel as it passes through the moderator region. A 100-kilogram force would be required to drive a 0.15-centimeter diameter wire into a cavity with a pressure of 5.07×10^{7} newtons per square meter. As it enters the cavity, the uranium instantly vaporizes and rises in temperature to about 55 000 K. Reactor startup could be achieved by first establishing the hydrogen flow. Next uranium particles would be blown into the dead cavity region to achieve nuclear criticality. The power would then be increased to a level sufficient to vaporize the incoming uranium rod.

The seeded hydrogen is heated solely by absorbing the thermal radiation from the fissioning uranium fireball. The cavity walls receive only about 1 or 0.5 percent of the thermal radiation from the fireball. This wall protection is accomplished by introducing about 1 percent by weight of a seeding material such as graphite or tungsten particles into the hydrogen. This same technique is used in the nozzle region to reduce the hydrogen radiation heat load and the hydrogen temperature near the nozzle wall to tolerable levels. Seed concentrations of about 1 to 10 percent are required here. Figure 1 shows that some cold hydrogen can be introduced through the nozzle walls directly from the plenum at the downstream end of the engine if it is required. This would tend to reduce the specific impulse.

SPECIFIC IMPULSE

The specific impulse of a gas-core rocket engine is limited by the fraction of the reactor power that reaches the solid, temperature-limited portions of the engine, and by how that heat is removed. It is an unavoidable characteristic of the nuclear fission process that about 7 to 10 percent of the energy release is high-energy gamma and neutron radiation that will go through the hydrogen gas but be stopped in the surrounding solid reactor structure.

This energy that is deposited in the moderator can be regeneratively removed by the incoming hydrogen propellant. There is, however, a limit to how much heat the hydrogen can accommodate. For a 3000-second specific impulse engine, 7 percent of the reactor power will heat all the hydrogen propellant to 2800 K before it enters the reactor cavity. To achieve a higher specific impulse would require the solid parts of the engine to operate at an unrealistically high temperature. If the reactor materials, including the porous cavity wall, were limited to a little over 1000 K and if only regenerative cooling were used, the specific impulse would be limited to 2000 seconds.

Higher specific impulses are possible by using an external radiator to reject part of the moderator heat to space. The radiator is shown schematically in figure 1. To bring the hydrogen into the reactor cavity at 1000 K for a specific impulse of 5000 seconds would require that the hydrogen remove no more than about 1 percent of the reactor power from the moderator, as shown in figure 2. The remaining 6 to 9 percent would have to be removed by the radiator loop.

The idea of using a radiator to achieve high-specific-impulse, gas-core engines is not new. It was discussed by the author of reference 8 about 10 years ago. Although the principle was never in question, the practicality of employing it was. The general idea that a space radiator for a gas-core engine would be either prohibitively big or heavy prevented serious consideration of the concept until recently. The use of lightweight compact radiator systems developed for space power systems (ref. 9) with low-thrust, but high-specific-impulse, systems now makes this old idea quite attractive.

It appears that the ultimate limitation on specific impulse of a gas-core engine will depend on the ability to absorb the thermal radiation from the fuel in the hydrogen so that the cavity wall and the nozzle wall do not receive an excessive heat flux. Based on current estimates of the optical absorption and emission properties of the gases involved, a recent Lewis in-house study indicates that the maximum specific impulse is in the range 5000 to 7000 seconds. The energy transfer processes are quite involved, however, and more theoretical and experimental work will be required to determine with much reliability the specific impulse capability of a gas-core engine.

ENGINE WEIGHT

The engine weight analysis used for this study is the same as was presented in reference 4, except for the addition of a space radiator and the elimination of a specific equation for fuel volume as a function of the hydrogen- to uranium-mass-flow ratio. The engine weight is taken to be the sum of the individual weights of the moderator, pump, nozzle, pressure shell, and radiator:

$$W_e = W_m + W_p + W_n + W_s + W_r \tag{1}$$

An initial series of calculations were made to select a "best" cavity diameter and moderator thickness combination. This preliminary optimization was done at values of specific impulse (5000 sec) and thrust (4.4×10^4 N) that are centered in the ranges covered in this study. One cavity diameter and one moderator thickness were selected on this basis, and then held constant for all subsequent variations of specific impulse and thrust. Thus, after this initial reactor optimization, the moderator weight was not a variable in this study.

Engine Pressure

In order to calculate the weights of the nozzle, turbopump, and pressure shell, it was necessary to calculate the pressure required to have a critical mass in the engine. This was obtained from the following equation:

$$P = 14.6 \frac{M_c^{1.385} F^{0.383} I_{sp}^{0.383}}{D_c^{4.54} V_F^{1.51}} \tag{2}$$

where P is the reactor pressure in atmospheres, M_c is the critical mass in kilograms, F is the engine thrust in newtons, I_{sp} is the specific impulse in seconds, D_c is the reactor cavity diameter in meters, and V_F is the fraction of the reactor cavity filled with fuel. Equation (2) is more general than the form used in reference 4 where a specific relation between fuel volume fraction and hydrogen- to uranium-mass-flow ratio was used to eliminate V_F from equation (2). The present study was carried out for a fuel volume fraction of 0.25. Recent fluid mechanics experiments using air/air indicate that this value should be attainable for hydrogen- to uranium-flow ratios in the range 100 to 400.

Nozzle, Turbopump, and Pressure Shell

These components were evaluated using the same weight equations given in reference 4. They are as follows:

Nozzle:

$$W_n = 5 \frac{F}{P} \tag{3}$$

Pump:

$$W_p = 0.875 \frac{FP^{2/3}}{I_{sp}} \tag{4}$$

Shell:

$$W_s = 140P\left(\frac{R_s}{8.5}\right)^3 \tag{5}$$

where the component weights are in kilograms, F is thrust in newtons, I_{sp} is specific impulse in seconds, P is reactor pressure from equation (2) in atmospheres, and R_s is the inside radius of the pressure shell in meters.

The radiator weight estimate was based on a recent study (ref. 9) of a vapor-fin for space power systems. The vapor-fin design in reference 9 would weigh 290 kilograms per megawatt of radiated power, based on operating the radiator at 945 K. For this study it was assumed that the same radiator, or at least one of the same weight per unit surface area (19 kg/m^2 of plan form area), could be operated at 1100 K. This gives a weight of 145 kilograms per megawatt of radiated power:

$$W_r(\mathrm{kg}) = 145\ Q_r \tag{6}$$

Equations (2) to (6) were used to obtain the weight of each engine component. Equation (1) was used to obtain the total engine weight. For this study, calculations were carried out for specific impulses of 3000, 5000, and 7000 seconds, and for engine thrusts from 4.4×10^3 to 4.4×10^5 newtons.

It may be necessary to operate the radiator at a pressure less than that of the reactor cavity in order to keep the lightweight vapor-fin design. For example, the pressure stress in the radiator tube walls used in the design of reference 9 would range from 10.14×10^7 to 50.7×10^7 newtons per square meter for internal tube pressures ranging from 10.14×10^6 to 5.07×10^7 newtons per square meter, respectively. This same pressure stress range could be reduced by a factor of 3 by increasing the tube wall thickness such that the overall radiator weight would increase by about 20 percent. In an actual engine design, one might not choose to do this, but instead operate the radiator at a lower pressure than that of the reactor. This would then require a pump to increase the radiator discharge pressure to that inside the reactor pressure vessel.

RESULTS AND DISCUSSION

The engine weight results are presented and discussed in this section. First, the effect of varying the cavity diameter and the moderator thickness is presented. Based on these results, one cavity diameter and one moderator thickness are selected for the remainder of the calculations. For this fixed engine geometry, the effect of thrust level on engine weight is determined for a specific impulse of 5000 seconds. Next, the effect of specific impulse on engine weight is presented over a range of thrust levels. Finally, these results are presented in terms of a parameter commonly used to describe low-thrust propulsion devices, engine specific mass, which is the ratio of engine weight to thrust power (in kg/kW).

Effect of Cavity Diameter and Moderator Thickness

Changes in cavity diameter or in moderator thickness cause two effects on engine weight. One effect is that the weight of moderator material is changed. The other effect is that the uranium density required for criticality is changed. This changes the required reactor pressure, which, in turn, results in a change in the pressure shell weight.

These two influences on engine weight tend to oppose each other. For example, reducing the moderator thickness reduces the moderator weight, but increases the pressure required for criticality. Thus, there is some optimum moderator thickness that gives a minimum engine weight. It is possible, however, that the engine pressure at this minimum-weight geometry would be unrealistically high, so that one might choose to operate at some near but off-optimum configuration that has a somewhat lower pressure.

Engine weight was calculated for five combinations of cavity diameter and moderator thickness. The results are shown in figure 3. The critical mass requirements used were taken from reference 7 and are listed in table I. These engine weight calculations were carried out for a specific impulse of 5000 seconds and a thrust level of 4.4×10^{4} newtons. Both of these values are centered within the ranges covered in this study.

Cavity diameters of 2.4, 3.6, and 4.9-meters were used with a constant moderator thickness of 0.76 meter. Moderator thicknesses of 0.61, 0.76, and 0.91 meter were used with a constant cavity diameter of 3.6 meters. Within these ranges, reductions in either parameter caused a decrease in engine weight but an increase in engine pressure. A cavity diameter of 2.4 meters with a moderator thickness of 0.76 meter produced the lightest engine, which weighed 64 000 kilograms. The reactor pressure for this engine was 7.8×10^{7} newtons per square meter.

Further reduction of cavity diameter below 2.4 meters would probably have produced a slightly lighter engine, but at the expense of an extremely high pressure. This is shown in figure 4. On the basis of these results, a 2.4-meter cavity diameter and a 0.76-meter moderator thickness were selected as representing a near-optimum engine configuration. The remaining calculations were carried out using this one engine geometry.

Effect of Thrust Level on Engine Weight

Higher thrust requires a heavier engine. The component weights are shown in figure 5 for engine thrust varying from 0 to 1.1×10^{5} newtons at a specific impulse of 5000 seconds. For a thrust below about 5×10^{4} newtons, the radiator weight is not too important, compared to the moderator and the pressure shell weights. At a thrust of 1.1×10^{5} newtons, the radiator, pressure shell, and moderator each contribute about one-third of the total engine weight.

For higher thrusts, the radiator weight begins to dominate. This is shown in table II. At a thrust of 2.2×10^{4} newtons, the radiator only contributes 6400 kilograms to the total engine weight of 51 000 kilograms, or about 12 percent. At a thrust of 2.2×10^5 newtons, the radiator accounts for 64 000 kilograms out of 133 000 kilograms, or almost 50 percent. This indicates that for thrusts above 2.2×10^5 newtons, at this specific impulse of 5000 seconds, significant weight reductions can be achieved if higher temperature radiators can be developed. For example, the radiator weight could be cut in half by operating at 1300 K instead of 1100 K. All the calculations of this study were done for a radiator temperature of 1100 K.

Effect of Specific Impulse on Engine Weight

Higher specific impulses require heavier engines, at a given thrust level. This is shown in figure 6. For a thrust of 4.4×10^4 newtons, engine weights of 50 000, 64 000, and 73 000 kilograms are required for specific impulses of 3000, 5000, and 7000 seconds, respectively.

At a specific impulse of 3000 seconds, a radiator may not be necessary. If the hydrogen propellant enters the reactor at 2800 K, it can regeneratively remove all the gamma and neutron heat deposition from the moderator region. This produces a lighter engine, as shown by the dashed curve in figure 6. Whether one would actually choose to operate the moderator at a little over 2800 K in order to achieve the lower weight would depend on a number of factors, such as the particular mission involved and the effect of moderator temperature on engine reliability and life. The solid curves in figure 6 are based on a hydrogen cavity inlet temperature of 1400 K. Table III lists the percent of reactor power that must be radiated away for this temperature.

Gas-Core Specific Mass

For low-acceleration systems such as electric thrusters, it is useful to characterize the propulsion device in terms of its specific mass. This parameter α is in kilograms of powerplant weight per kilowatt of thrust power. It can be related to the engine thrust-weight ratio as follows. The thrust power, or jet power as it is sometimes called, is given by $1/2\ (F\times I_{sp}\times g)$, which is simply the kinetic energy in the jet exhaust. Using this relation, the specific mass α, in kilograms per kilowatt, is

$$\alpha = \frac{20.9}{I_{sp}\left(\frac{F}{W_e}\right)} \tag{7}$$

where the specific impulse is in seconds and the engine thrust-weight ratio is dimensionless.

Figure 7 shows the results of the present study presented on this basis. The specific mass of a gas-core engine varies from a high of 0.6 to a little less than 0.02 for specific impulses from 3000 to 7000 seconds and thrust levels from $4.4 \times 10^{+3}$ to $4.4 \times 10^{+5}$ newtons. Higher specific impulse or higher thrust produces a lower, and therefore better, specific mass.

SUMMARY OF RESULTS

An analysis has been carried out to determine the characteristics of a low-thrust, high-specific-impulse, gas-core, nuclear rocket engine. The latest information on reactor critical mass requirements, radiant-heat-transfer properties, and fluid mechanics were used. For specific impulses above 3000 seconds, it was necessary to incorporate a space radiator as an engine system component. Engine weight was calculated for specific impulses ranging from 3000 to 7000 seconds, and for thrust levels from 4.4×10^{3} to 4.4×10^{5} newtons. Radiator weight estimates were based on an operating temperature of 1100 K. The calculations indicate the following results:

1. Gas-core engines have the potential of producing a specific mass in the range 0.6 to 0.02 kilogram of weight per kilowatt of thrust power.

2. For a specific impulse of 5000 seconds and a thrust of 1.1×10^{5} newtons, engine weight is estimated to be 91 000 kilograms. This weight is composed of about equal proportions of radiator, moderator, and pressure shell weights. For the entire range of specific impulses and thrust levels of this study, engine weight varied from 35 000 to 380 000 kilograms.

3. Engine weight increases with increasing specific impulse and with increasing thrust level. For a given specific impulse, higher thrust-weight ratios occur at higher thrust levels because engine weight does not increase as fast as the thrust does.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 8, 1971,
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TABLE I. - GAS-CORE ENGINE CRITICAL

MASSES AND MODERATOR WEIGHTS

Cavity diameter, m	Total moderator thickness, m	U^{233} critical mass, kg	Moderator weight, kg
2.4	0.76	26	28 000
3.6	0.61	54	41 000
	.76	46	55 000
	.91	43.5	70 000
4.9	0.76	90	85 000

TABLE II. - CHARACTERISTICS OF 5000-SECOND-

SPECIFIC-IMPULSE GAS-CORE ENGINE

[Cavity diameter, 2.4 m; moderator thickness, 0.76 m; radiator temperature, 1100 K.]

Engine thrust, N	Reactor power, MW	Weight, kg			
		Engine (total)	Pressure shell	Radiator	Moderator
2.2×10^{4}	750	51 000	17 000	6 400	28 000
4.4	1 500	64 000	22 000	13 000	↓
1.1×10^{5}	3 750	91 000	31 000	31 000	↓
2.2	7 500	133 000	41 000	64 000	↓
4.4	15 000	210 000	53 000	127 000	↓

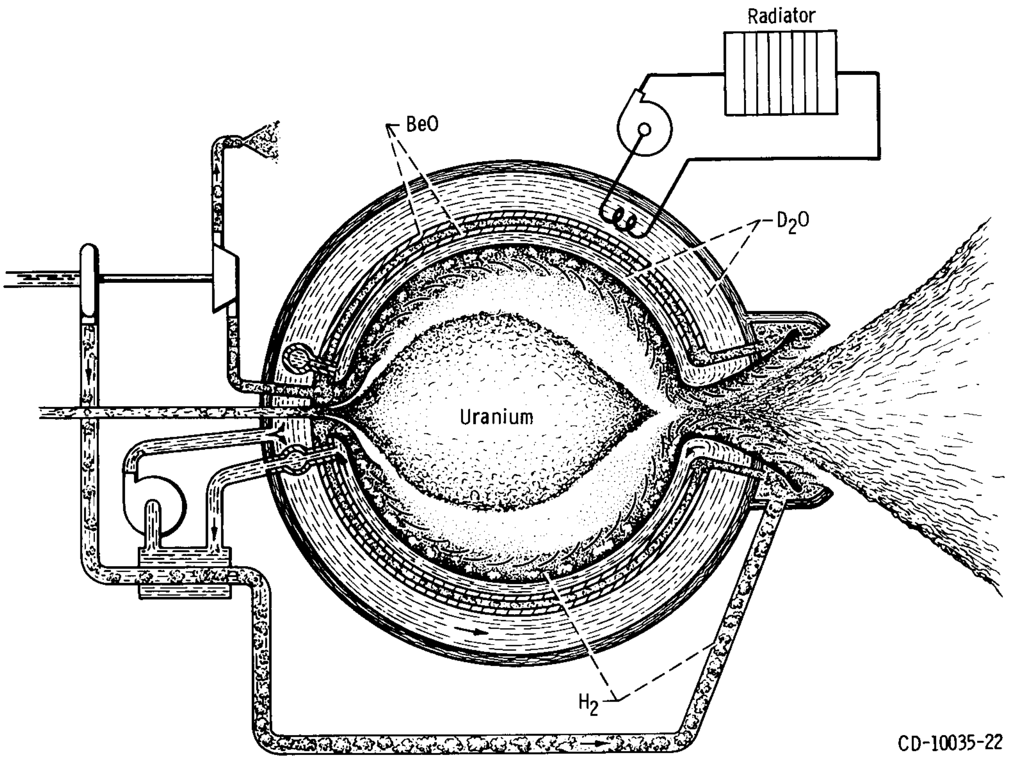
TABLE III. - GAS-

CORE-ENGINE

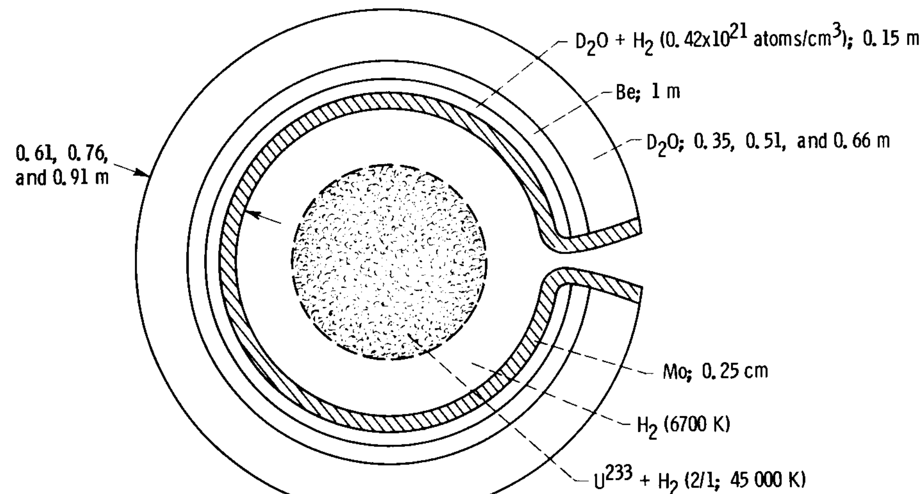
RADIATOR LOAD

[Hydrogen cavity inlet temperature, 1400 K.]

Specific impulse, I_{sp}, sec	Percent of reactor power radiated
3000	3.7
5000	5.9
7000	6.5



(a) Conceptual sketch.



(b) Model for nuclear calculations.

Figure 1. - High-specific-impulse, gas-core engine.

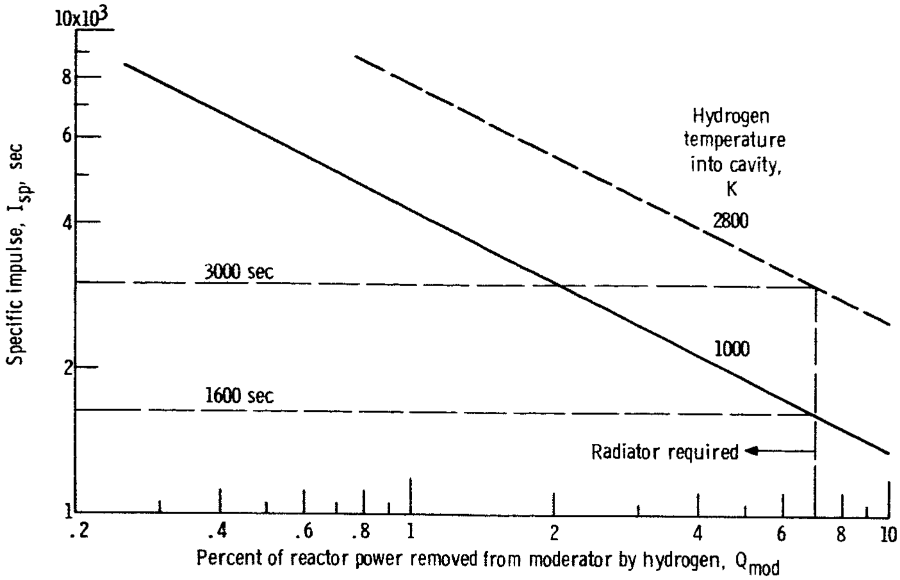


Figure 2. - Gas-core engine specific impulse.

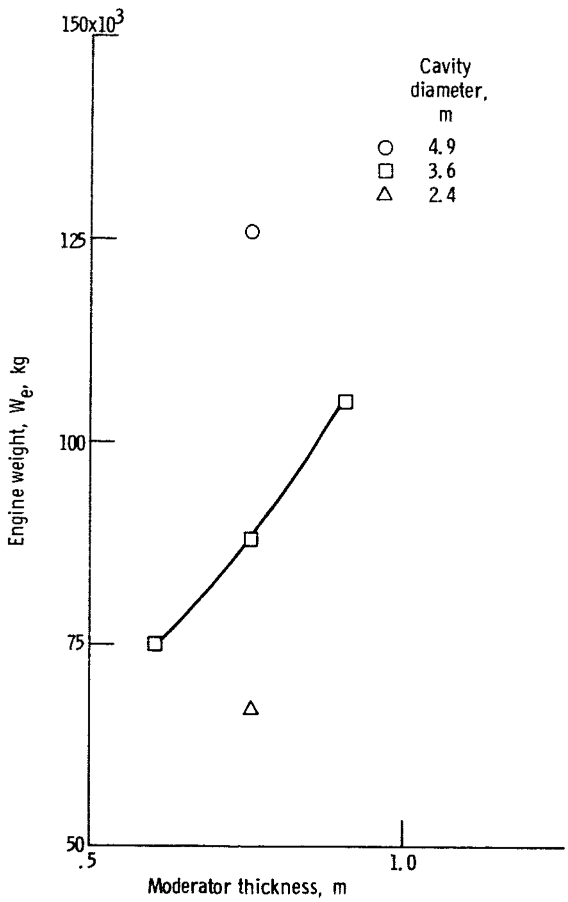


Figure 3. - Engine weight for gas-core nuclear rocket. Specific impulse, 5000 seconds; thrust, 4.4×10^4 newtons.

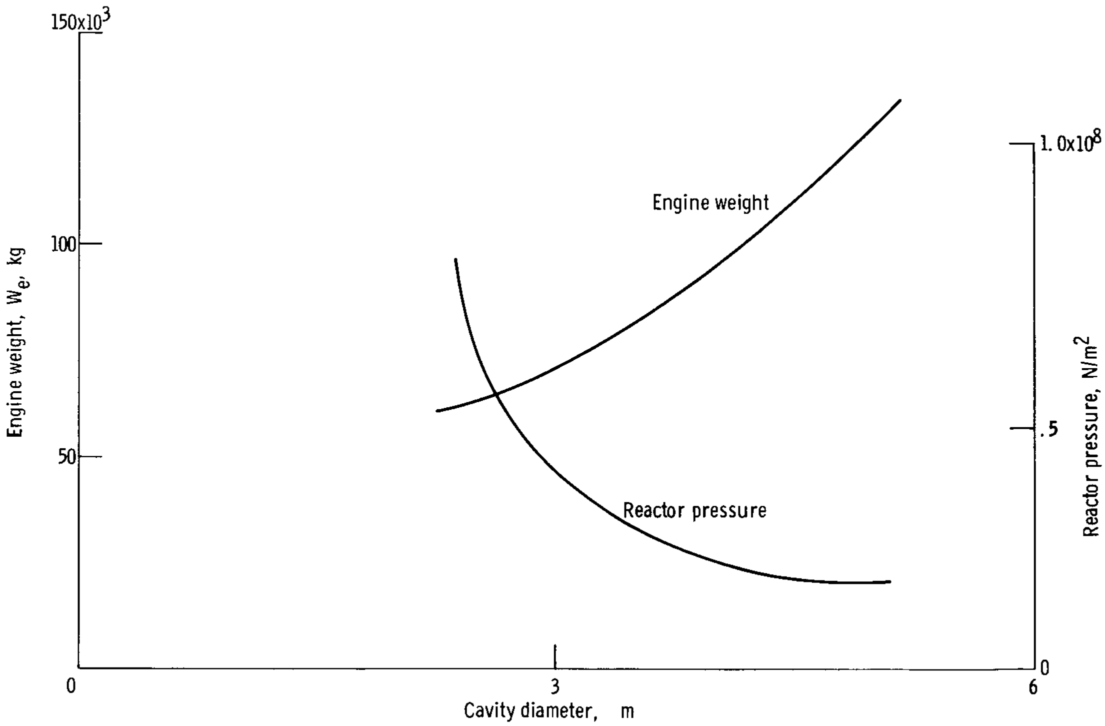


Figure 4. - Effect of cavity size on engine weight. Moderator thickness, 0.76 meter; specific impulse, 5000 seconds; thrust, 4.4×10^4 newtons.

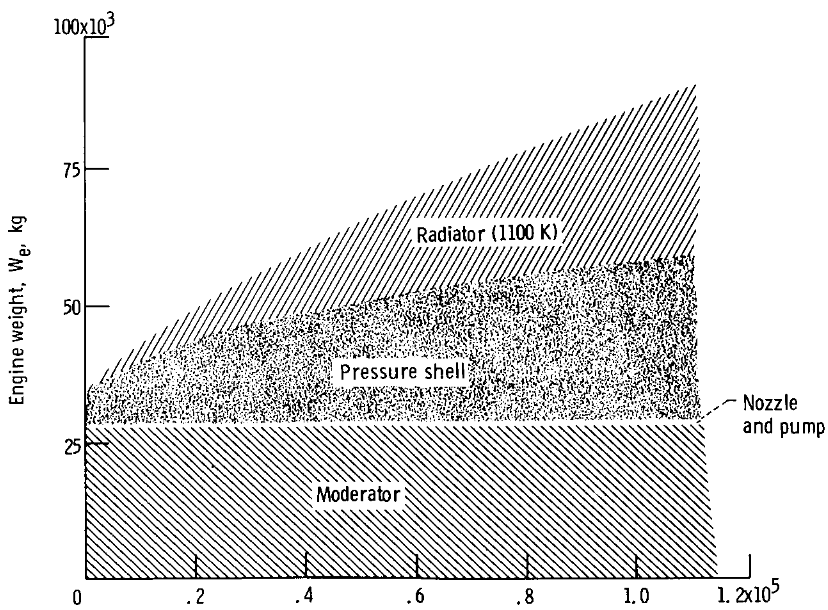


Figure 5. - Engine weight breakdown for 5000-second-specific-impulse, gas-core engine.

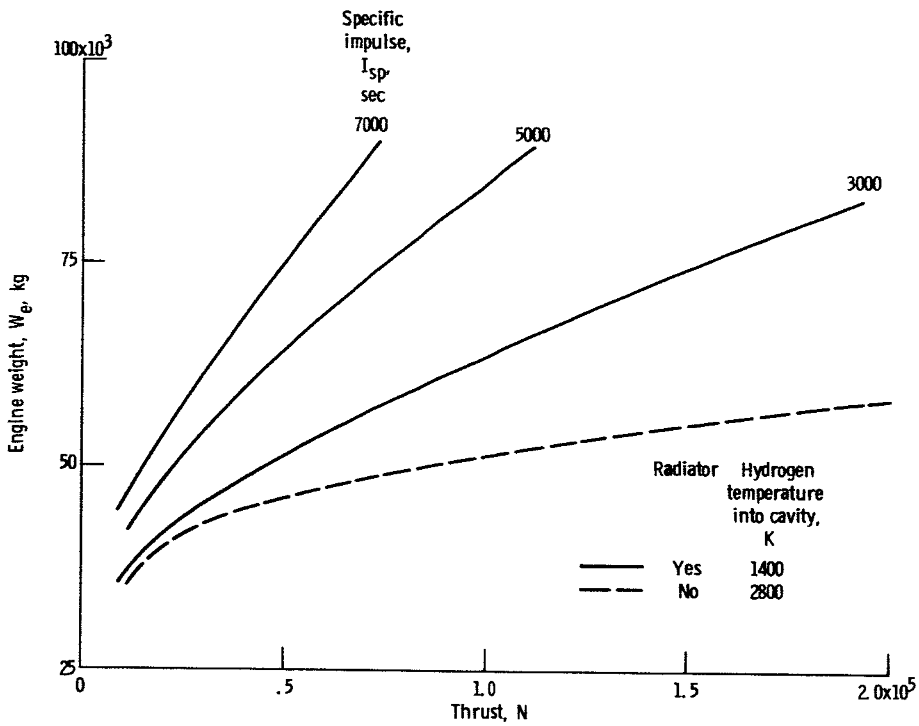


Figure 6. - Engine weights for various specific impulses. Radiator temperature, 1100 K.

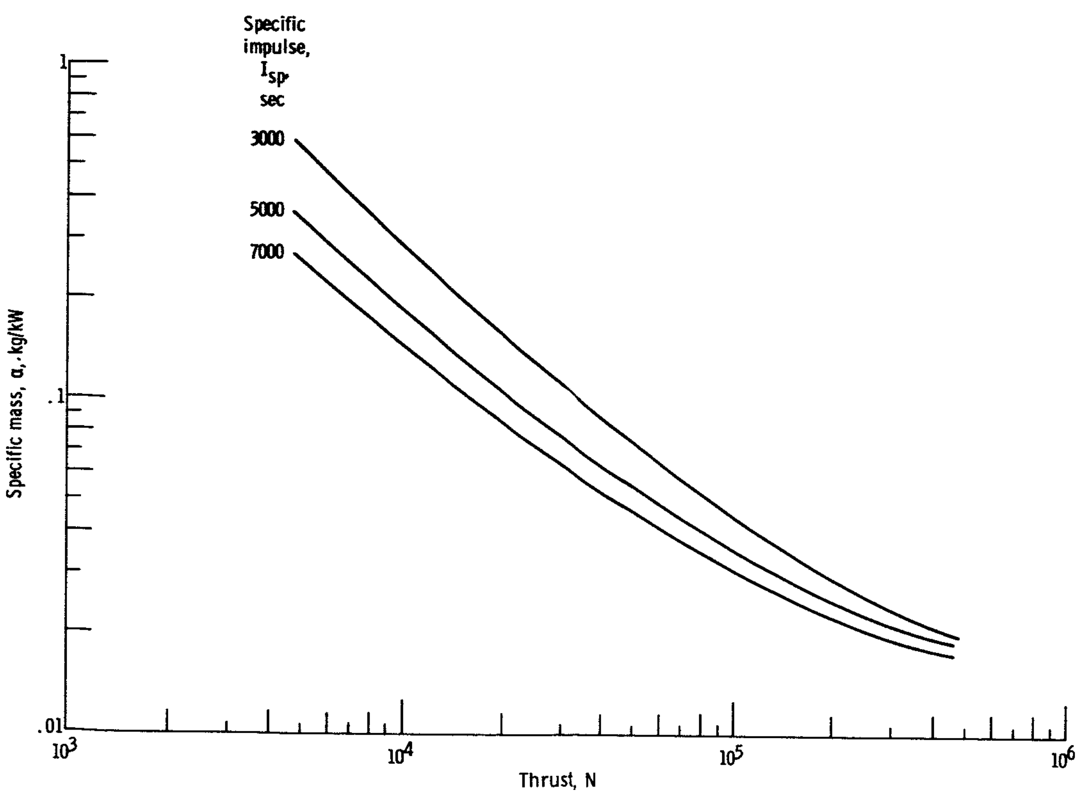


Figure 7. - Gas-core engine specific mass.